

Function and Dysfunction of Human Sinoatrial Node

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Sinoatrial node (SAN) automaticity is jointly regulated by a voltage (cyclic activation and deactivation of membrane ion channels) and Ca^{2+} clocks (rhythmic spontaneous sarcoplasmic reticulum Ca^{2+} release). Using optical mapping in Langendorff-perfused canine right atrium, we previously demonstrated that the β -adrenergic stimulation pushes the leading pacemaker to the superior SAN, which has the fastest activation rate and the most robust late diastolic intracellular calcium (Ca_i) elevation. Dysfunction of the superior SAN is commonly observed in animal models of heart failure and atrial fibrillation (AF), which are known to be associated with abnormal SAN automaticity. Using the 3D electroanatomic mapping techniques, we demonstrated that superior SAN served as the earliest atrial activation site (EAS) during sympathetic stimulation in healthy humans. In contrast, unresponsiveness of superior SAN to sympathetic stimulation was a characteristic finding in patients with AF and SAN dysfunction, and the 3D electroanatomic mapping technique had better diagnostic sensitivity than corrected SAN recovery time testing. However, both tests have significant limitations in detecting patients with symptomatic sick sinus syndrome. Recently, we reported that the location of the EAS can be predicted by the amplitudes of P-wave in the inferior leads. The inferior P-wave amplitudes can also be used to assess the superior SAN responsiveness to sympathetic stimulation. Inverted or isoelectric P-waves at baseline that fail to normalize during isoproterenol infusion suggest SAN dysfunction. P-wave morphology analyses may be helpful in determining the SAN function in patients at risk of symptomatic sick sinus syndrome.

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KEY WORDS: Calcium; Sinoatrial node; Adrenergic beta-agonists; Sick sinus syndrome; Biological pacemaker.

Introduction

The sinoatrial node (SAN) automaticity is essential for maintaining normal cardiac function. Sick sinus syndrome is an abnormality involving the generation of the action potential by the SAN and is characterized by an atrial rate inappropriate for physiological requirements. The sick sinus syndrome occurs in 1 of every 600 cardiac patients older than 65 years and accounts for approximately

half of implantations of pacemakers in the United States.¹⁾ A better understanding of the mechanisms of SAN automaticity and sick sinus syndrome is therefore clinically important. The SAN automaticity is maintained by synergistic actions of a "voltage clock" mediated by voltage-sensitive membrane ionic currents such as the hyperpolarization-activated pacemaker current (I_h)²⁾ and a " Ca^{2+} clock" mediated by rhythmic spontaneous sarcoplasmic reticulum Ca^{2+} release.³⁾ While extensive work has been performed to document the interactions of voltage and Ca^{2+} clocks of the SAN in animal models, translating these findings to human patient care is difficult. Our review will focus on the translational studies of human SAN function.

Pacemaker Hierarchy and the Importance of Ca^{2+} Clock in an Intact Sinoatrial Node

Cardiac automaticity at the organ level is very complex. In addition to cellular mechanisms, integrative anatomical and physiological factors are involved in cardiac pacemaking. The intact SAN is a heterogeneous structure that includes multiple different cell types

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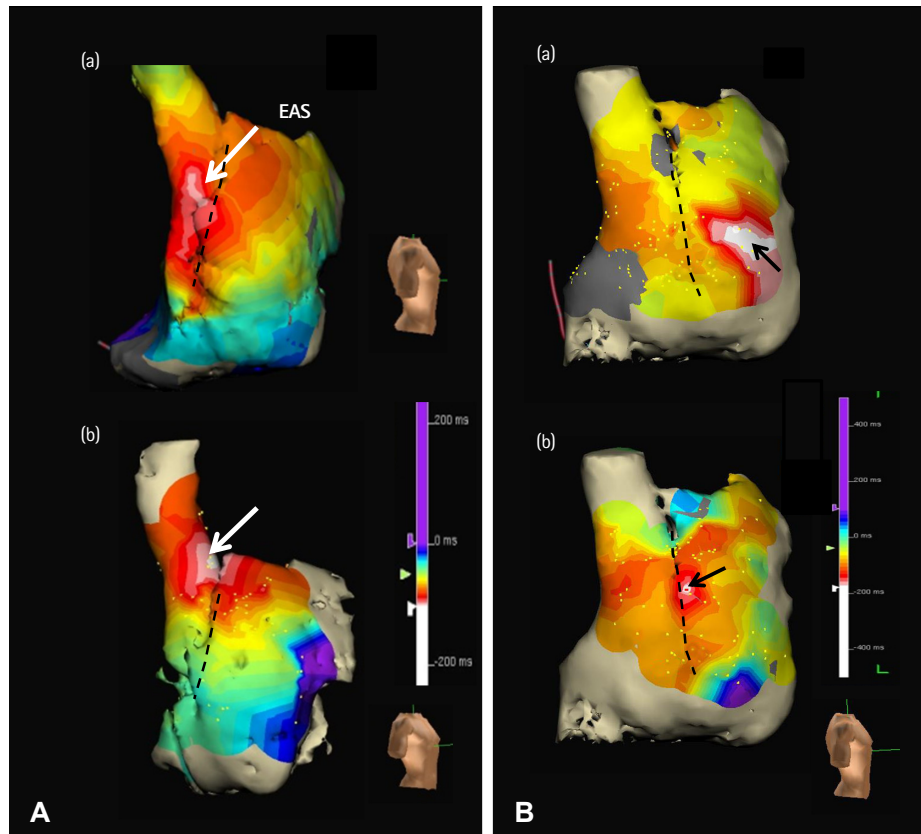


Fig. 1. Effects of isoproterenol infusion on EAS. A: cranial shift of the EAS in a healthy control patient. The EAS at baseline (a) was in the superior one-third of crista terminalis (CT). The EAS during isoproterenol infusion (b) was at the junction between the SVC and the RA. B: impaired cranial shift of the EAS in an AF patient with symptomatic bradycardia. The EAS at baseline (a) was ectopic (at the RA free wall). The EAS during isoproterenol infusion (b) was located at the mid one-third of CT. The superior SAN in this patient was inactive with or without isoproterenol. The dashed line in each panel marks the CT. EAS: earliest atrial activation site, SVC: superior vena cava, RA: right atrial, AF: atrial fibrillation, SAN: sinoatrial node. Modified with permission from Joung et al.²⁶⁾

interacting with each other.⁴⁻⁶⁾ The Ca^{2+} clock in the superior SAN is primarily responsible for rate acceleration during sympathetic stimulation.⁷⁻¹¹⁾ However, the relative importance of the voltage and Ca^{2+} clocks for pacemaking in different regions of the SAN, and in response to neurohumoral stimuli such as β -agonists, may be different. Indeed, activation maps in intact canine right atrium (RA) have shown that the SAN impulse origin is multicentric,¹²⁾ and sympathetic stimulation predictably results in a cranial (superior) shift of the pacemaking site in human and dogs.¹³⁾¹⁴⁾ Based on evidence from isolated SAN myocytes, late diastolic Ca_i elevation relative to the action potential upstroke is a key signature of pacemaking by the Ca^{2+} clock.¹⁵⁻²⁰⁾ The same phenomenon could provide insights into the relative importance of the Ca^{2+} and voltage clock mechanisms in pacemaking in intact RA tissue,⁷⁾ subsidiary pacemakers²¹⁾²²⁾ or diseased state.²³⁾²⁴⁾

Mapping of Earliest Atrial Activation Site in Humans

Schuessler et al.¹⁴⁾ reported in a canine model that sympathetic

stimulation in general tends to induce a cranial shift in the location of the pacemaker within the pacemaker complex. With the development of 3 dimensional (3D) endocardial electroanatomical mapping techniques, it is possible to define the activation patterns within the human atria to accurately locate the earliest atrial activation site (EAS).²⁵⁾ If the findings in canine models are applicable to humans, then the superior SAN should vigorously respond to sympathetic stimulation and serve as the dominant pacemaker during sympathetic stimulation. Indeed, EAS of control human subjects shifted cranially during isoproterenol infusion (Fig. 1A).²⁶⁾ These findings indicate that in both canine models and humans, the superior SAN is primarily responsible for heart rate acceleration during sympathetic stimulation in patients with normal SAN function.

Sinoatrial Node Function in Patients with Atrial Fibrillation and Symptomatic Bradycardia

Atrial fibrillation (AF) is associated with significant electrophysiological and structural remodeling of the atria, and is often associated

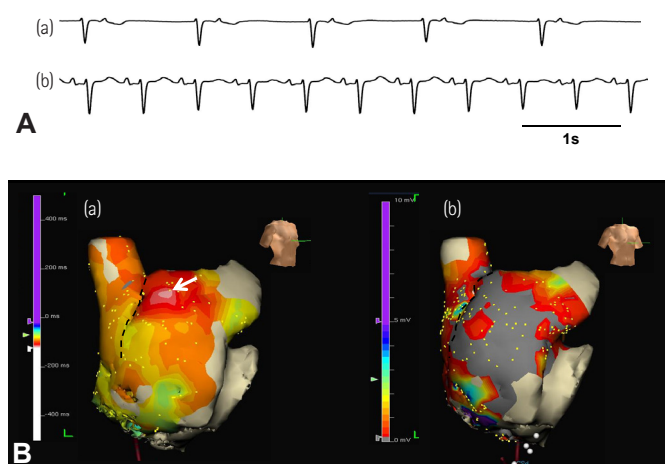


Fig. 2. The different leading pacemaker sites during heart rate acceleration. A 50-year-old woman had long-standing persistent AF and SAN dysfunction. A: (a) Junctional rhythm of 40 bpm after termination of AF. (b) Sinus P-wave appeared and sinus rate increased to 110 bpm during isoproterenol infusion of 10 μ g/min. B: (a) RA activation map. The superior crista terminalis was recovered as the EAS (arrow) during isoproterenol infusion. (b) RA voltage map. The middle and lower part of RA and crista terminalis is a low voltage area with gray color (<0.5 mV). AF: atrial fibrillation, SAN: sinoatrial node, RA: right atrial, EAS: earliest atrial activation site. Modified with permission from Joung et al.²⁶⁾

with sick sinus syndrome.²⁷⁾²⁸⁾ The SAN dysfunction may be reversible after successful catheter ablation of AF.²⁹⁾ In dogs, persistent (>2 weeks) rapid atrial pacing and chronic AF resulted in SAN dysfunction, as evidenced by prolongation of the SAN recovery time and decreases in the intrinsic heart rates.³⁰⁾ Unresponsiveness of the Ca^{2+} clock in the superior SAN to sympathetic stimulation is a characteristic finding in dogs with AF and heart failure.³¹⁾³²⁾ Consistent with that found in a canine model,³¹⁾ the patient with AF with SAN dysfunction had impaired heart rate acceleration and absence of upward shift of the EAS during isoproterenol stimulation (Fig. 1B). These findings suggest that Ca^{2+} clock malfunction underlies these abnormal physiological responses to isoproterenol infusion.

The Cranial Shift of the Earliest Atrial Activation Site and Sinoatrial Node-Right Atrium Propagation

Previous studies have shown that the impulse from the SAN propagates into RA through an upper and a lower exit site.³³⁾ It is possible that isoproterenol preferentially shifts the exit site to the upper portion of the SAN instead of the activation of the superior SAN by the activation of Ca^{2+} clock. Because the extracellular electrograms cannot be used to differentiate SAN activation and RA activation, the shifting of SAN exit sites and the shifting of the actual pacemaking sites may look the same on the 3D map. The data from our human 3D mapping study cannot be

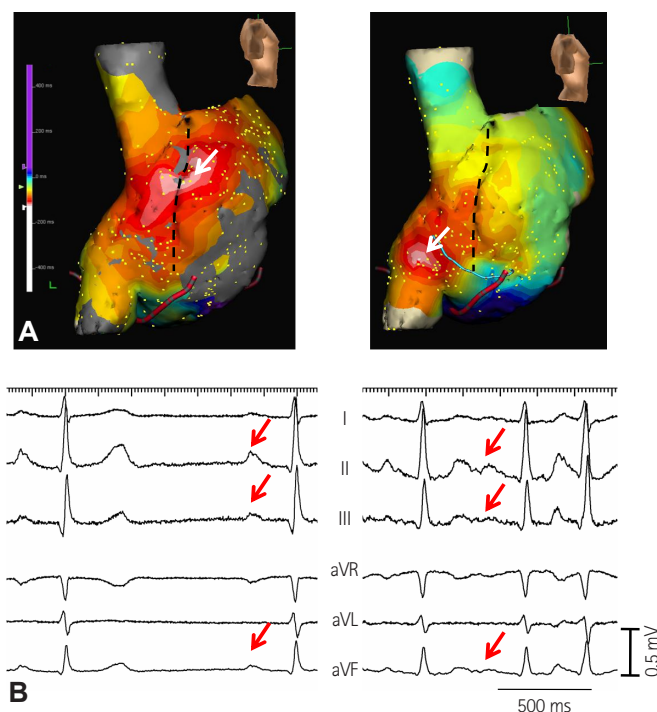


Fig. 3. Inferior shift of EAS during isoproterenol infusion in a patient taking amiodarone. A: RA activation map at baseline (left panel) and during isoproterenol infusion (right panel). EAS was shifted to the lower part of crista terminalis (arrow) during isoproterenol infusion. B: EKG at baseline (left panel) and during isoproterenol infusion (right panel). Note the decreased amplitude of P-waves in leads II, III, and aVF after inferior shift of EAS during isoproterenol infusion (arrows). EAS: earliest atrial activation site, RA: right atrial. Modified with permission from Mun et al.³⁹⁾

used to differentiate these two mechanisms.²⁶⁾ However, we found that isoproterenol infusion reactivates the pacemaker in the superior SAN in several patients with extensive RA fibrosis and junctional rhythm at baseline (Fig. 2). In these patients, changing the sinoatrial node-right atrium exit pathway is clearly not a mechanism of upward shift of the EAS. Moreover, in other patients with upward shifting of EAS during isoproterenol infusion, the conduction between SAN to RA occurred at multiple directions, without evidence of conduction delay along the crista terminalis or the septum. Based on these findings and the mapping of the Ca^{2+} clock activity in the canine models, we propose that the pacemaker hierarchy is likely to be created by differential responses of Ca^{2+} clock to sympathetic tone at different portions of the SAN rather than changing the exit from a fixed pacemaking site.

Sinoatrial Node Dysfunction and Amiodarone

As the elderly population continues to expand, AF is becoming an increasingly common medical condition.³⁴⁻³⁷⁾ Amiodarone is the most frequently used agent for maintaining sinus rhythm in patients with AF. Amiodarone impairs SAN function in one-third of

patients and is associated with an increased risk of pacemaker insertion.³⁸⁾ Our study also showed that amiodarone induced SAN dysfunction in one-fourth of patients without SAN dysfunction at baseline.³⁹⁾ Amiodarone caused impaired heart rate acceleration and impaired cranial shift of EAS after sympathetic stimulation (Fig. 3).³⁹⁾ Therefore, Ca^{2+} clock malfunction of the superior SAN might be related with impaired heart rate acceleration and cranial shift of the pacemaking site. Amiodarone inhibits multiple ion channels (I_{Tox} , I_{Kr} , I_{Ks} , I_{CaT} , I_{Na}) and is a beta adrenergic blocker.⁴⁰⁾ Because amiodarone is a potent blocker of I_{CaT} ,⁴⁰⁾ it may suppress the Ca^{2+} clock in the SAN.⁴¹⁾ In addition, amiodarone can inhibit the sympathetic activity. A downward shift of the EAS has been reported in human patients after esmolol infusion.²⁵⁾ Therefore, the beta blocking effects of amiodarone may also influence the location of the EAS. Amiodarone may induce hypothyroidism, and this effect may, in part, decrease SAN function.³⁸⁾ Finally, Turker et al.⁴²⁾ recently showed that amiodarone inhibits the small-conductance calcium-activated K (SK) channel. Because the SK channel is important in SAN and atrioventricular node function,^{43/44)} SK channel inhibition may affect SAN automaticity.

Unicentric versus Multicentric Activation

Sanders et al.⁴⁵⁾ previously reported that multicentric activation is found both in normal control and heart failure. However, the EASs are more numerous in normal control (average 4 sites) than in heart failure (average 2.5 sites). They also reported that the SAN complex in patients with SAN dysfunction is more often unicentric, localized to the lower crista terminalis at the site of the largest residual voltage amplitude.⁴⁵⁾ We also found that most healthy control patients had multicentric SAN activation pattern (Fig. 1A), and that the number of EAS in AF patients is smaller than that in healthy controls (Fig. 1B). A reduction of the EAS suggests that there are fewer backup pacemaking sites to respond to sympathetic stimulation, which could be a sign of SAN dysfunction.

P-Wave Morphology and the Earliest Atrial Activation Site

The P-wave morphology has been used to identify the origins of focal atrial tachycardias with a high sensitivity and specificity.^{46/47)} Fig. 4 shows that compared with sinus rhythm (arrows), atrial tachycardia originating from the inferior part of crista terminalis had smaller amplitude of P-wave in leads II, III, and aVF (broken arrows). We found that the distances from the superior vena cava-right atrial junction to the EAS were negatively correlated with the amplitude of P-wave in inferior leads. If the EAS was shifted to the

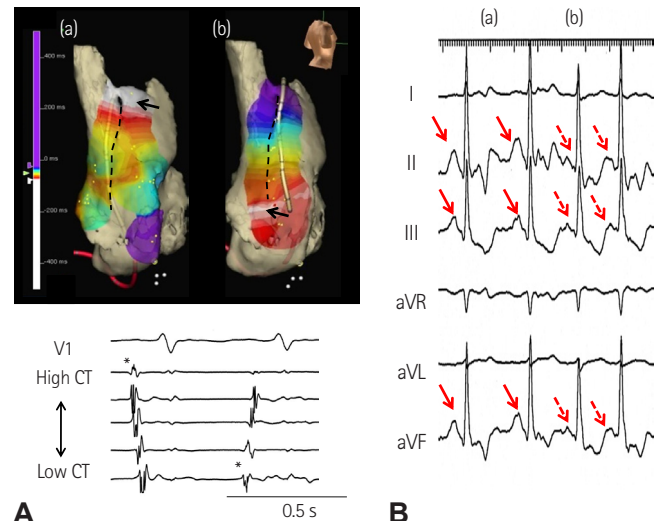


Fig. 4. Atrial tachycardia originating from lower crista terminalis. A: RA activation map showing sinus beat (a) and atrial tachycardia (b) from superior and inferior crista terminalis, respectively. B: EKG showing sinus beat (a) and atrial tachycardia (b). Atrial tachycardia originating from lower crista terminalis had decreased amplitude of P-waves in leads II, III, and aVF. RA: right atrium, CT: crista terminalis.

superior part of crista terminalis or superior vena cava, the P-wave amplitudes were increased in most of the patients without SAN dysfunction.³⁹⁾ In contrast, the shift of the EAS to the inferior part of crista terminalis or inferior vena cava was related with decreased P-wave amplitude in inferior leads in patients with SAN dysfunction (Fig. 5A). These findings suggest that the change of P-wave morphology in inferior leads during isoproterenol infusion can be used to assess the superior SAN responsiveness to isoproterenol infusion. Patients with SAN dysfunction showed low amplitude of P-waves at baseline and during sympathetic stimulation (Fig. 5B).

Comparative Efficacy of Testing for Symptomatic Bradycardia

We analyzed the comparative efficacy of corrected sinoatrial node recovery time (CSNRT) and 3D mapping in differentiating AF patients with and without sinus bradycardia. CSNRT > 550 ms is considered a positive CSNRT test. The failure of superior SAN to serve as EAS during isoproterenol infusion is considered a positive 3D mapping test (Fig. 6). The sensitivity, specificity, positive predictive efficacy, and negative predictive efficacy of the CSNRT test are 35%, 89%, 45% and 84%, respectively (Fig. 6A), and of the 3D mapping test are 78%, 78%, 47% and 93%, respectively (Fig. 6B). The 3D mapping test was twice as sensitive but slightly less specific than the CSNRT test in detecting AF patients with sinus bradycardia. However, both tests have limitations as they are invasive

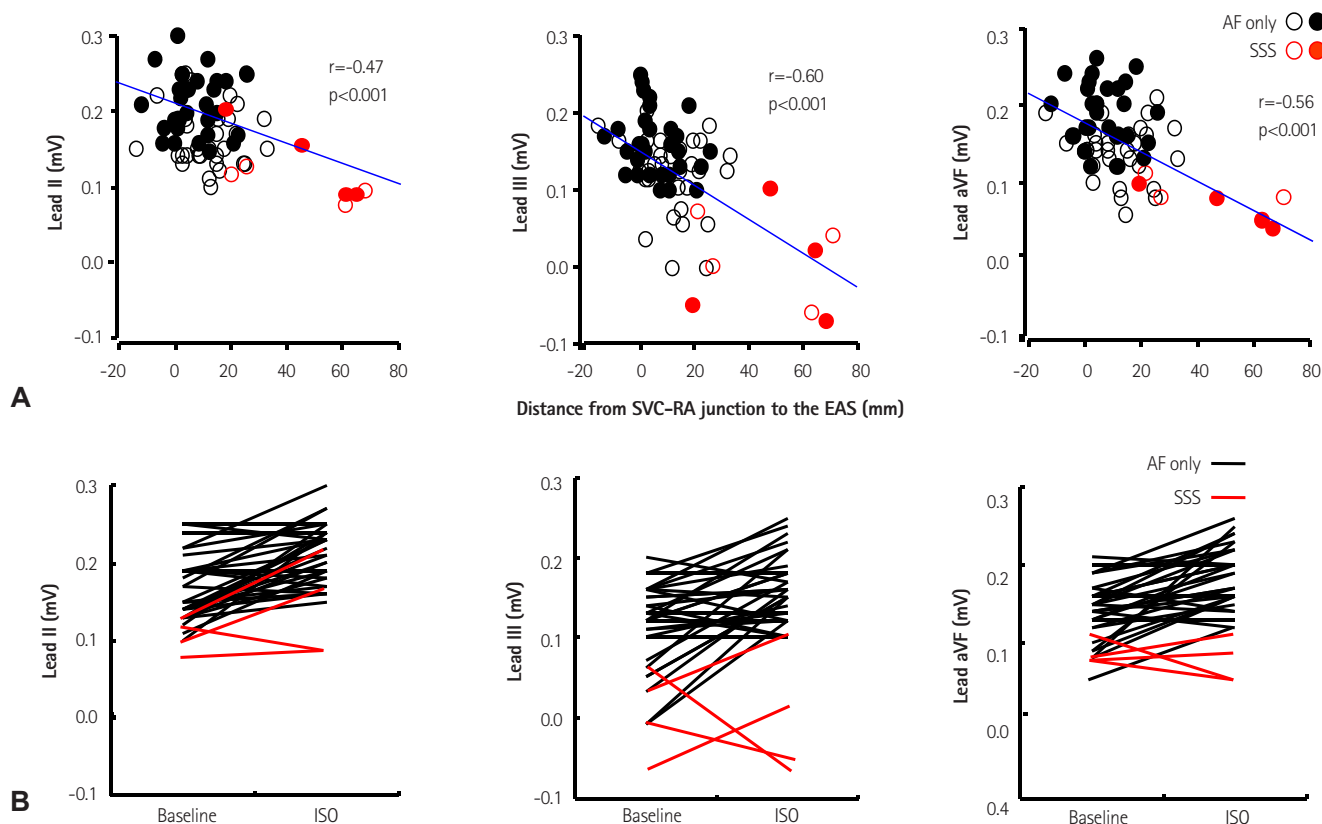


Fig. 5. The P-wave changes induced by sympathetic stimulation. A: the negative correlation between the distance from the SVC-RA junction to the most cranial EAS and P-wave amplitude in leads II (left panel), III (middle panel), and aVF (right panel). Unfilled and filled circles represent P-wave amplitude at baseline and during isoproterenol infusion, respectively. Black and red circles represent the patients without and with sick sinus syndrome (SSS), respectively. B: the change of P-wave amplitude in leads II (left panel), III (middle panel), and aVF (right panel) during isoproterenol infusion. Note that the patients with SSS tend to have low P-wave amplitude and low EAS location both at baseline and during isoproterenol infusion. SVC-RA: superior vena cava-right atria, EAS: earliest atrial activation site, aVF: , ISO: isoproterenol. Modified with permission from Mun et al.³⁹⁾

and time consuming tests.

Recently, we analyzed the poor increase in inferior P-wave amplitude during sympathetic stimulation for the diagnosis of sick sinus syndrome. The poor increases of P-wave amplitude of lead aVF (<0.1 mV) during isoproterenol infusion showed a sensitivity of 78% and specificity of 89% for the diagnosis of sick sinus syndrome. Finally, the combined algorithm using CSNRT of >550 ms and poor increases of P-wave amplitude of lead aVF showed further improved diagnostic accuracy (sensitivity of 89% and specificity of 76%).

Recent Basic Researches on Sinoatrial Node Automaticity

Calmodulin-dependent protein kinase II (CaMKII) has emerged as a central regulator of physiological SAN responses and a key determinant of SAN dysfunction.⁴⁸⁾ The calcium and CaMKII is especially important for physiological "fight or flight" SAN beating rate responses.⁴⁹⁾ Inhibition of CaMKII in SAN does not affect baseline

heart rate, but reduces heart rate increases in response to physiological stress. Excessive CaMKII activity, as occurs under pathological conditions such as heart failure, ischemia, and diabetes, can promote intracellular Ca^{2+} overload and reactive oxygen species production. Nicotinamide adenine dinucleotide phosphate oxidase is activated in conditions with increased angiotensin II, leading to oxidation of two methionine residues of CaMKII, rendering the enzyme autonomously active. Increased CaMKII activation leads to SAN cell death, reducing the threshold volume of automatic cells of the SAN and increasing non-excitable tissue in the form of fibrosis. CaMKII-induced apoptosis results in SAN cell loss, which disrupts the normal source-sink balance leading to sinoatrial node dysfunction.⁵⁰⁾⁵¹⁾ In a canine heart failure model, increased expression of adenosine receptors within the SAN region together with increased fibrosis have been reported to be related with the loss of synchrony and sinoatrial node dysfunction.⁵²⁾ A source-sink mismatch caused by cell loss has been observed in a mouse model of diabetes and in ankyrin-B syndrome.⁵³⁾⁵⁴⁾

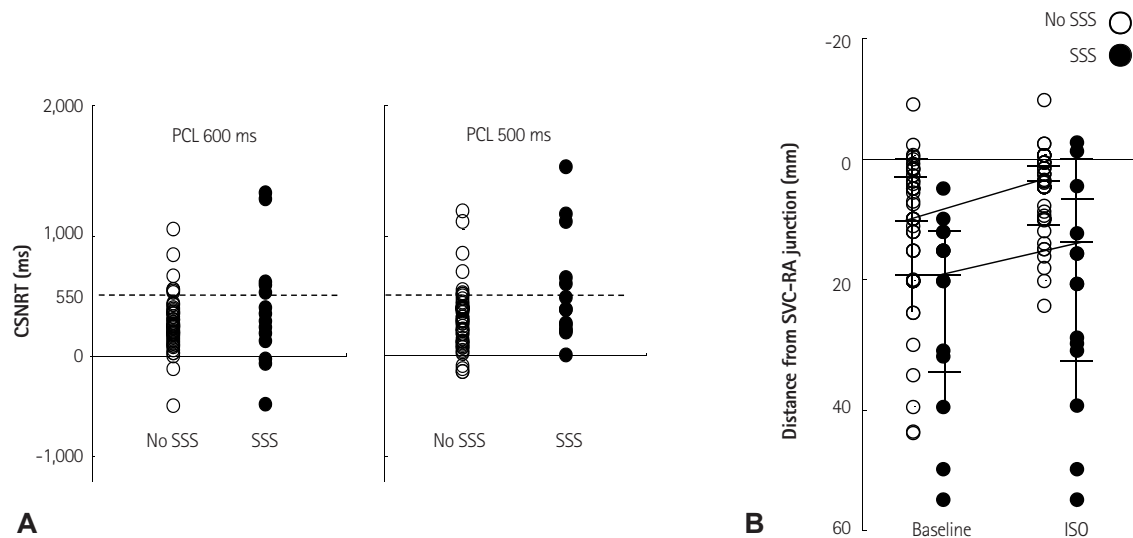


Fig. 6. Comparative Efficacy of Testing for Symptomatic Bradycardia. A: the dot plots of the CSNRT from AF patients without (No SSS) and with sinus bradycardia (SSS) at each pacing cycle length (PCL) showing large overlaps between the two groups. The dashed line shows the CSNRT of 550 ms. B: the distance from the SVC-RA junction to the most cranial earliest activation site at baseline and during isoproterenol infusion. CSNRT: corrected sinoatrial node recovery time, AF: atrial fibrillation, SSS: sick sinus syndrome, SVC-RA: superior vena cava-right atrial, ISO: isoproterenol. Modified with permission from Joung et al.²⁶⁾

Conclusion

The voltage and Ca^{2+} clocks jointly regulate SAN automaticity. In various models of sick sinus syndrome, the dysfunction of superior SAN during sympathetic stimulation was consistently observed. In human 3D mapping, superior SAN was identified as the leading pacemaker site during sympathetic stimulation. However, unresponsiveness of superior SAN to sympathetic stimulation was commonly observed in patients with sinus dysfunction. 3D mapping, which showed unresponsiveness of the superior SAN or inferior P-wave amplitude, was more sensitive than classic CSNRT in identifying patients with sinus dysfunction. These novel tools obtained from basic research might help to diagnose sick sinus syndrome.

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